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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2686

EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER THROUGH LAMINAR AND TURBULENT BOUNDARY LAYERS ON A COOLED FLAT PLATE AT A MACH NUMBER OF 2.4

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SUMMARY

Wind-tunnel tests of the heat-transfer characteristics of the laminar and turbulent boundary layers on a cooled flat plate were conducted at a nominal Mach number of 2.4. Data were obtained for a Reynolds number range of 1.5×10^5 to 3×10^6 and for nominal surface temperatures of -40° F to 45° F with recovery temperatures of the order of 65° F.

The temperature-recovery factor, obtained from the heat-transfer data, agreed well with previous experimental flat-plate results. For the case of a laminar boundary layer, the results were independent of the Reynolds number with an average value of 0.884. For the case of a turbulent boundary layer, the average value was 0.906. Within the transition region, the results showed considerable scatter, with values ranging from 0.90 to 0.97.

The heat-transfer data were obtained with a negative temperature gradient along the plate over a major portion of the test region of the plate. For the case of laminar boundary layers, the negative surface-temperature gradients were found to have a strong effect on the heat-transfer coefficients, producing values considerably higher than would be expected for a constant-temperature surface. The results, when related to the constant-temperature case by means of a theoretical analysis, were generally in good agreement with theoretical results for constant-temperature surface. For the case of turbulent boundary layers the heat-transfer coefficients were in excellent agreement with theoretical results, and the negative surface-temperature gradients were found to have little effect.

INTRODUCTION

It is important to be able to calculate the heat-transfer characteristics of supersonic vehicles with a reasonable degree of accuracy since surface temperatures and heat-transfer rates in future missiles and airplanes may attain values which would affect significantly the vehicle structure and contents. Such calculations require knowledge of the nature of the boundary-layer-flow condition (i.e., whether laminar or turbulent) and of the adiabatic wall temperature or recovery factor.

At present, only limited experimental data are available on the heat-transfer characteristics of bodies which may be applicable to supersonic vehicles. The purpose of this investigation is to enlarge the fund of such data through tests of a flat plate at supersonic velocities.

A number of experimental results on the temperature-recovery factors on cones and bodies of revolution have been obtained for the case of laminar boundary layers, and the agreement with theoretical results is good (references 1 and 2). Experimental data for the temperature-recovery factors for the case of laminar boundary layers on flat plates are presented in references 3 and 4, and there is some difference between these results and those for cones. For the case of the turbulent boundary layer there are some experimental results for both flat plates and bodies of revolution (reference 3). These results agree well, but more data covering a wider range of variables are still required.

In the case of heat transfer through laminar boundary layers on flat plates and cones, the theory can be considered nearly complete. Corroborative experimental results are still relatively meager except for the case of heat transfer from cones. The theoretical and experimental work done prior to 1947 is summarized conveniently in references 5 and 6. Subsequent analyses have been performed, among others, by Chapman and Rubesin (reference 7), and Lighthill (reference 8). These two references have extended laminar-boundary-layer theory to the case of arbitrary distribution of surface temperature; and the latter also includes, for the incompressible case, an arbitrary distribution of local free-stream velocity. Heat transfer through laminar boundary layers on bodies of revolution has been studied in a number of investigations (references 1, 9, 10, and 11).

Knowledge of the heat-transfer characteristics of bodies with turbulent boundary layers in supersonic flows is meager. Theoretical considerations have been obstructed by insufficient information concerning the detailed mechanism of turbulence and relatively few experimental

investigations have been performed. Theoretical results have been presented in references 5, 12, and 13; experimental results have been presented in references 1, 5, and 12.

The present report presents heat-transfer and temperature-recovery-factor data for laminar and turbulent boundary layers obtained from a cooled flat plate in a supersonic air stream of Mach number 2.4. A flat-plate model was chosen since little data for flat plates are available; also a constant local free-stream velocity was desired since available theories predominantly consider this case. These data are compared with available theoretical and experimental results.

NOTATION

a local speed of sound, feet per second

A plate surface area, square feet

c_p specific heat of air at constant pressure, Btu per pound, $^{\circ}F$

c_v specific heat of air at constant volume, Btu per pound, $^{\circ}F$

g gravitational force per unit mass, 32.2 feet per second, second

h local heat-transfer coefficient, Btu per second, square foot, $^{\circ}F$

k thermal conductivity, Btu per second, square foot, $^{\circ}F$ per foot

M Mach number $\left(\frac{U}{a}\right)$, dimensionless

Nu Nusselt number $\left(\frac{hx}{k}\right)$, dimensionless

Pr Prandtl number $\left(\frac{g\mu c_p}{k}\right)$

q heat-transfer rate, Btu per second

r recovery factor $\left(\frac{T_{aw}-T_1}{T_0-T_1}\right)$

Re Reynolds number $\left(\frac{U_1 x}{\nu}\right)$, dimensionless

t temperature, $^{\circ}F$

T temperature, $^{\circ}F$ absolute

U air velocity parallel to plate, feet per second

x distance along plate from leading edge, feet

y distance normal to plate surface, feet

γ ratio of specific heats $\left(\frac{c_p}{c_v}\right)$, 1.40 for air, dimensionless

δ boundary-layer thickness, feet

θ boundary-layer momentum thickness, feet

μ absolute viscosity, pound-seconds per square foot

ν kinematic viscosity $\left(\frac{\mu}{\rho}\right)$, square feet per second

ρ mass density, slugs per cubic foot

Subscripts

aw adiabatic-wall conditions

w wall or surface conditions

1 free-stream conditions

o stagnation conditions

DESCRIPTION OF EQUIPMENT

Ames 6-Inch Heat-Transfer Tunnel

The Ames 6-inch heat-transfer tunnel used for this investigation has been described in detail in reference 3.

The Flat-Plate Model

The flat-plate model (fig. 1) spanned the test section of the tunnel and was supported such that its median plane was coincident with the

plane of symmetry of the test section. The model consisted of a fabricated steel body, 3/4 inch thick, containing the coolant passageways; a plastic sheet 5-1/2 by 13 inches containing the instrumentation; a 1-3/4-inch-long steel nosepiece with a 10° leading-edge angle; and plastic sheathing over the rest of the steel body for thermal insulation. The measured roughness of the plate surface was an average of 70 microinches from the mean profile. Air leakage between the model and the tunnel walls was prevented by sealing with thin rubber strips.

Heat meters were installed for measuring the heat-transfer rates. They were constructed in a manner similar to that described in reference 14 and were 3/8 inch wide and 1-1/2 inches long and located at 1/2-inch intervals along the plate with the first meter located 2 inches from the plate leading edge. The plastic sheet containing the heat meters was sandwiched by cementing between two 1/64-inch plastic sheets. The completed assembly was approximately 3/64 inch thick.

Ten copper-constantan thermocouples were installed for determining the plate-surface temperature. The first three, at 0.75, 1.25, and 1.50 inches from the leading edge, were installed in the nosepiece by peening them into holes drilled from the under side to within 1/32 inch of the top surface. The remaining seven thermocouples were placed in grooves cut in the under side of the plastic heat-meter assembly when it was cemented to the main steel body of the plate. These thermocouples were located at 2.20, 2.84, 3.84, 4.84, 6.34, 7.84, 9.34, and 10.84 inches from the leading edge of the plate.

The calibration of the flat-plate model was performed using a guarded heat source which produced known quantities of heat per unit time through the plate surface. Heat-flow rates through the heat meters were obtained in terms of their voltage outputs. The seven thermocouples imbedded in the plastic measured a temperature other than the surface temperature. The difference between the temperature measured by the thermocouples and the temperature of the surface was determined by calibration in terms of the heat-meter voltages. The surface temperature thus was calculated by adding the temperature measured by the thermocouples to the temperature difference between the thermocouples and the plate surface.

Cooling System

The cooling system for the flat plate consisted of a 2-ton refrigeration machine, a circulating pump, a thermostatically controlled mixing valve, and alcohol as the coolant. The mixing valve controlled the alcohol temperature at any temperature between 25° F and -50° F by

controlling the quantities of alcohol that flowed through and bypassed the refrigeration machine. When the coolant system was near thermal equilibrium the mixing valve controlled the alcohol temperature at any desired value within its range to 1/2° F.

TEST PROCEDURE AND ACCURACY

The test conditions covered a Reynolds number range based on length along the plate of 150,000 to 3 million, and a surface-temperature range of -40° F to 45° F. The Reynolds number range was obtained by varying the stagnation pressure from 2 to 36 pounds per square inch absolute. The surface-temperature variation was obtained by varying the alcohol temperature. The wind-tunnel stagnation temperature was maintained at a value of 93° ± 1° F for all the tests.

The Mach number distribution along the plate was determined from static-pressure and impact-pressure measurements. The equipment used and the procedure followed for these tests have been described in reference 12.

It was not possible to attain adiabatic conditions on the plate surface for the purpose of determining the recovery temperature; therefore, the recovery temperatures were evaluated from the heat-transfer data by extrapolation of the heat-transfer rates as a function of the ratio of the plate-wall temperature to the stagnation temperature to zero heat-transfer condition. The extrapolation at each position along the plate was carried out along a straight line determined by the method of least squares. The corresponding recovery factors were then calculated using the following equation:

$$r = 1 - \frac{T_o - T_{aw}}{T_o} \left[\frac{2}{(\gamma - 1) M_1{}^2} + 1 \right] \tag{1}$$

The validity of this extrapolation depends on the heat-transfer coefficients being independent of the surface temperature of the plate.

The local heat-transfer coefficients were calculated from the equation

$$h = \frac{q/A}{t_w - t_{aw}} \tag{2}$$

where the heat-transfer rates and the plate-surface temperatures were calculated using the heat meter and thermocouple voltages and the calibration data; the recovery temperatures, t_{aw}, were determined as noted above.

When the heat-transfer measurements were completed, velocity determinations were made in the boundary layer of the plate using the same techniques and instruments as those described in reference 12.

The estimated accuracy of the experimental measurements are presented in the following table:

Quantity	Estimated maximum error	Basis of estimate
q/A	±5-1/2 percent	maximum spread in calibration data
t_w	±4° F	calculated using maximum value of q/A occurring in tests and maximum error in q/A
t_{aw}	±1.5° F	maximum spread in data
r	±0.01	calculated from equation (1)
$\frac{Nu}{RePr^{1/3}}$	±10 percent	maximum spread of data
M	±0.01	precision of measurements
Re	±0.75 percent	precision of measurements

DISCUSSION OF RESULTS

Mach Number Distribution on Flat-Plate Model

The Mach number distributions on the flat-plate model are shown in figure 2 for four stagnation pressures. The increase in the Mach number with increasing stagnation pressure is believed to be due to a change in the effective-area ratio of the nozzle which is caused by changes of the thickness of the boundary layer on the tunnel walls and model. The maximum variation in the Mach number along the plate at any particular stagnation pressure is 0.08, which is a 3-percent variation. Thus, theoretical results for flat plates should apply since the local free-stream Mach number, or velocity, is essentially constant.

Surface Temperatures and Heat-Transfer Rates

Three plate-surface-temperature and heat-transfer-rate distributions are presented in figure 3 for stagnation pressures of 6, 16, and 36 pounds per square inch absolute. These are representative of all the data obtained. The first three temperature-data points on each of the figures are for the steel nosepiece and are generally higher than the temperatures farther back along the plate since the nosepiece was relatively uncooled. Figure 3(a) shows data for conditions such that the boundary layer was believed to be laminar over the entire test length. For a stagnation pressure of 16 psia (fig. 3(b)), the boundary layer is believed to be laminar up to about 4-1/2 inches where the beginning of transition is indicated by the sudden increase in the heat-transfer rate and the rise in surface temperature. At 36 psia stagnation pressure (fig. 3(c)), transition has begun at less than 2 inches and ends approximately at 3-1/2 inches. This is indicated by the increasing heat-transfer rate from 2 to 3-1/2 inches and the gradual decrease in heat-transfer rate from 3-1/2 to 5 inches.

A shock wave originating at the leading edge of the plate was reflected from the upper wall of the tunnel and was incident on the surface of the plate at approximately 7-1/2 inches from the leading edge of the plate. The effect of this shock wave on the boundary layer depended on the strength of the shock wave which, in turn, depended on the stagnation pressure. From figure 3(a) it can be seen that the shock wave at 6 psia stagnation pressure has very little effect on the boundary layer, while at 36 psia stagnation pressure (fig. 3(c)) the effect is quite pronounced, as indicated by the rise in heat-transfer rate at 7-1/2 inches, and appears to extend upstream to about 5-1/2 inches. Because of this the data have not been used for positions along the plate of 6 inches and beyond.

Boundary-Layer Velocity Profiles

In figure 4 are presented two representative experimental boundary-layer velocity distributions which were used for corroboration of the type of boundary layer as deduced from the heat-transfer data. The two velocity distributions were obtained at 5-1/2 inches from the leading edge and for stagnation pressures of 6 and 36 psia. The theoretical velocity distributions corresponding to these conditions were obtained from references 7 and 12, respectively. The experimental velocity distributions agree sufficiently well with the theoretical ones to identify the boundary layers as laminar and turbulent. Heat-transfer data corresponding to these velocity distributions are presented in figures 3(a) and 3(c). Since identification of the type of boundary layer from the

heat-transfer data was corroborated for these typical cases, the procedure of identifying the type of boundary layer from the heat-transfer data is believed to be valid for the whole of the data.

Temperature-Recovery Factor

Typical experimental data are presented in figure 5 with heat-transfer rates as a function of the ratio of surface temperature to stagnation temperature for three values of the stagnation pressure. For each position along the plate, the data points are located very nearly on a straight line. This indicates that, for the range of surface temperature involved, the heat-transfer coefficients are independent of either the surface temperature or the temperature potential causing heat transfer, since the heat-transfer coefficients are related to the slopes of these lines. Thus extrapolation of these data to zero heat-transfer rates for the purpose of determining the recovery temperature seems valid.

Figure 6 presents the temperature-recovery factors as a function of Reynolds number. This Reynolds number is based on the distance from the leading edge of the plate and on air properties evaluated at the free-stream static temperature. The data indicate that the temperature-recovery factor for a laminar boundary layer is essentially constant with a value of 0.884 ± 0.006 which is 2 percent and 3-1/2 percent higher, respectively, than the theoretical values of $(Pr^{1/2})_1$ and $(Pr^{1/2})_w$. The agreement with the experimental results of reference 3 is good, but the present results and those of reference 3 are 3-1/2 percent higher than experimental results ($r = 0.85$) obtained on cones (references 1 and 2). For the turbulent boundary layer the temperature-recovery factor is 0.906 ± 0.004 for Reynolds numbers from 2 to 3 million. These values are about 1 percent higher than the values presented in reference 3 and agree well with the theoretical value $(Pr^{1/3})_1$. For the transition zone, which extends from a Reynolds number of 1 to 2 million, the temperature-recovery factors exhibit considerable scatter ranging from 0.90 to 0.98, and are higher than values for the laminar and turbulent boundary layers. These data are higher than the results from reference 3 for a transition boundary layer, but reference 1 has reported values ranging from 0.92 to 0.97. In general, the present results for temperature-recovery factors are higher than theoretical results and experimental results for cones (references 1 and 2). The reasons for these differences are not, at present, understood but might possibly be due to the differences in flow conditions over flat plates and cones, details of model construction, or wind-tunnel flow conditions such as air-stream turbulence level.

Heat-Transfer Results

The heat-transfer coefficients calculated from the experimental data are presented in figure 7. These results were obtained from tests at

4, 8, 16, 20, 28, and 36 psia stagnation pressures. For 4 and 8 psia stagnation pressures the boundary layer was all laminar and the heat-transfer coefficients decreased in value with increasing distance along the plate. At 16 psia stagnation pressure, transition from a laminar boundary layer to a turbulent one apparently begins at about 5 inches as indicated by the slight increase in value of the heat-transfer coefficients. At 20 and 28 psia stagnation pressures, transition is indicated as beginning at 4 and 3 inches, respectively. At 36 psia stagnation pressure, transition has begun ahead of 2 inches and ends at about 3 inches where the heat-transfer coefficients reach a maximum value and begin decreasing with increasing length along the plate.

Heat-transfer data are often correlated by means of the dimensionless expression $Nu/RePr^{1/3}$ as a function of Reynolds number (reference 15). The heat-transfer data of this investigation are presented in this form in figure 8 and are compared with theoretical curves computed from references 7 and 13. These dimensionless representations are of general value only for results obtained from a surface with a uniform temperature. The present results were obtained from a surface with a nonuniform temperature and cannot be compared directly with results for a surface with a uniform temperature. In order to compare these results with theoretical results for constant-surface temperature, the present data were related to the case of a surface with a uniform temperature by means of theoretical calculations described in reference 7 for the case of the laminar boundary layer and in reference 16 for the case of the turbulent boundary layer.

Figure 9 presents the heat-transfer correlation from figure 8 as related to the case of a constant-temperature surface. A comparison of the two figures indicates the effect of the nonuniform temperature of the surface on the heat-transfer coefficients. For the case of the laminar boundary layer the correction factor was a maximum of 50 percent for the results at 2 inches and 10 percent at 5 inches. It is to be noted that the correction factors applied to the data using results from reference 7 are only approximate, since the experimental temperature distributions along the plate surface were approximated with a sixth degree polynominal rather than a power series which is called for in the exact solution. This may have contributed somewhat to the scatter of the results for the laminar boundary layer in figure 9.

For the case of the turbulent boundary layer, the results are for positions 4 and 5 inches from the leading edge of the plate. At these positions the temperature of the surface had reached essentially constant values. Calculation using the method of reference 16 indicated that the data at 4 and 5 inches were affected less than 5 percent by the temperature gradients on the front portion of the plate. In view of the small magnitude of this temperature-gradient effect, no correction was applied and the values for the turbulent boundary layer are the same in figures 8 and 9. No attempt was made to correct the results within the transition region.

The results for the laminar boundary layer (fig. 9) agree to within 20 percent of the theoretical results with the exception of the data obtained at a position 2 inches from the leading edge of the plate which are 85 percent above the theoretical results. This large difference between the experimental and theoretical results at 2 inches could not be accounted for entirely by assuming a maximum plausible temperature discontinuity at the joint between the nosepiece and plate in applying the methods of references 6 and 7 but may have been due also to the effect on the flow of the leading edge and joint.

For a fully developed turbulent boundary layer occurring after a natural transition, the results converge with comparatively little scatter to the theoretical results for a constant-temperature surface presented by Van Driest (reference 13). The results for a turbulent boundary layer are limited to a rather small Reynolds number range and, thus, conclusions drawn from the results must be correspondingly restricted.

The theoretical analyses of the turbulent boundary layer on flat plates all consider the boundary layer as being turbulent from the leading edge. This was not the case for the present experiments as the turbulent portion of the boundary layer was preceded by a short length of laminar boundary layer and a natural-transition region. The good agreement, then, of the experimental data with the theoretical results (fig. 9) is therefore fortuitous. In order to investigate this, a further comparison of these experimental data with theoretical results was made. The boundary-layer momentum thickness, θ, at 5 and 5-1/2 inches from the leading edge and corresponding Reynolds numbers of 3.0 and 3.3 million, respectively, were determined from impact-pressure surveys through the boundary layer and used in forming a Reynolds number $(U_1\theta/\nu_1)$. Figure 10 presents the theoretical curve, obtained from reference 13, of Reynolds number based on the boundary-layer momentum thickness as a function of the Reynolds number based on the distance from the leading edge and two points determined from the experiments. The experimental points are approximately 25 percent below the theoretical curve indicating that the experimental turbulent boundary layer was thinner than the theoretical boundary layer, or, in effect, behaved as if the origin of the experimental boundary layer was some point downstream from the leading edge of the plate. Thus, the proper lengths for use in forming the Reynolds numbers should be the effective length of the turbulent boundary layer rather than the distance from the leading edge of the plate. A method for determining this effective length is described in reference 12. It is felt that, due to the lack of sufficient measurements of the boundary-layer momentum thickness and the limited Reynolds number range of the data, correcting the present data is unwarranted.

Figure 11 is a cross plot of figures 9 and 10 with $Nu/RePr^{1/3}$ plotted as a function of the Reynolds number based on the boundary-layer

momentum thickness. The symbols in figure 11 correspond to those in figure 10. The agreement of the experimental points with the theoretical curve is within 12 percent. The good agreement with theory of the experimental results presented in figures 9 and 11 seems anomalous in view of figure 10. However, it should be pointed out that the slope of the theoretical curve of $Nu/RePr^{1/3}$ as a function of the Reynolds number based on either the length of flow or the momentum thickness is so small that large changes in either Reynolds number are accompanied by relatively small changes in $Nu/RePr^{1/3}$. It should be noted that the experimental results are presented in the form $Nu/RePr^{1/3}$, which is equivalent to the form Nu/Re used in the theoretical analyses, since they consider a Prandtl number of 1.

The heat-transfer results (fig. 9) indicate that transition from a laminar boundary layer to a turbulent boundary layer begins and ends at Reynolds numbers of 1 and 2 million, respectively. These values are somewhat lower than those reported in reference 3. There was no noticeable stabilizing effect of the cooled surface on the laminar boundary layer. This is contrary to theoretical prediction and previous experimental results (reference 17). It is likely that no effect was noticed since the temperature range of the surface was small and measurements were obtained at relatively few stations along the plate.

The heat-transfer results exhibit some scatter in the transition region, but, in general, the values of $Nu/RePr^{1/3}$ increase smoothly with increasing Reynolds numbers from the values for a laminar boundary layer to the values for a turbulent boundary layer. In addition to the scatter of the data in the transition region, there was noticed during the tests a considerable unsteadiness in the heat-transfer rates. The heat meters generated steady voltages for a steady laminar boundary layer and for a steady turbulent boundary layer. In the transition region, however, the heat-meter voltages oscillated as much as ±5 percent about a mean value. The magnitude of the oscillations changed smoothly through the transition region reaching a maximum approximately in the middle of the region. The extent of the transition region as indicated by the heat-meter voltage oscillations corresponded in every case to the transition region as indicated by the heat-transfer data.

CONCLUSIONS

Based on tests of a cooled flat plate at a Mach number of 2.4 and a Reynolds number range of 0.15 to 3.1 million, the following conclusions were drawn:

1. Temperature-recovery factors for laminar and turbulent boundary layers agreed well with previous flat-plate results. The average value

for a laminar boundary layer was 0.884, and was independent of Reynolds number. The average value for a turbulent boundary layer was about 0.906 for Reynolds numbers from 2 to 3 million. The values within the transition zone showed considerable scatter and reached a maximum of 0.97 which is higher than previous flat-plate results.

2. The heat-transfer results for the laminar boundary layer, when reduced to the constant-temperature-surface case, agreed well with theoretical results except near the leading edge of the plate.

3. Heat-transfer results for a turbulent boundary layer were found to agree well with theory for a compressible turbulent boundary layer even though the presence of the laminar flow and natural transition regions are not considered by the theory.

4. The transition from a laminar boundary layer to a turbulent boundary layer as indicated by the heat-transfer data was found to begin at a Reynolds number of 1 million and end at a Reynolds number of 2 million.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Feb. 1, 1952

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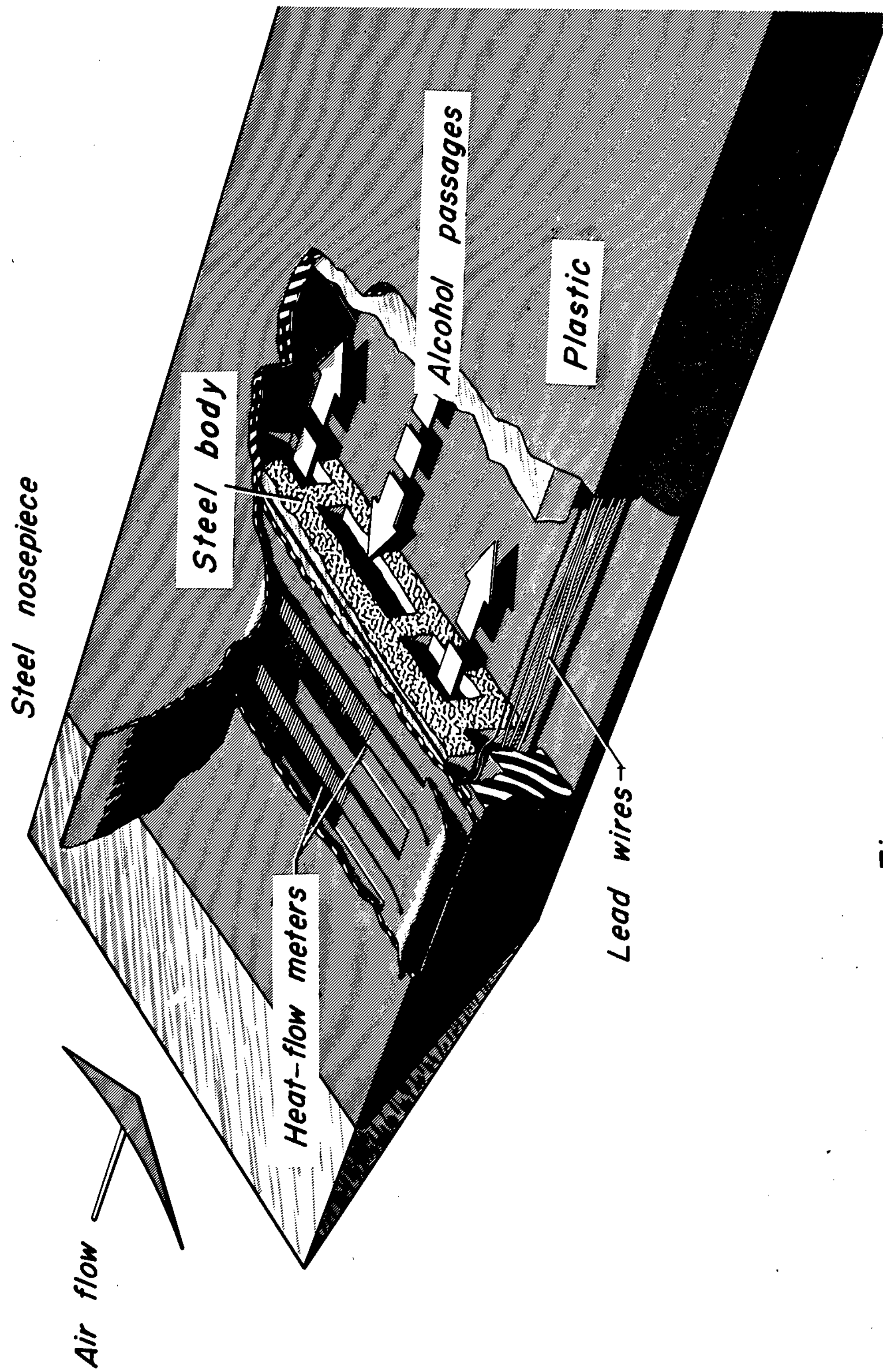


Figure 1. — Flat-plate model.

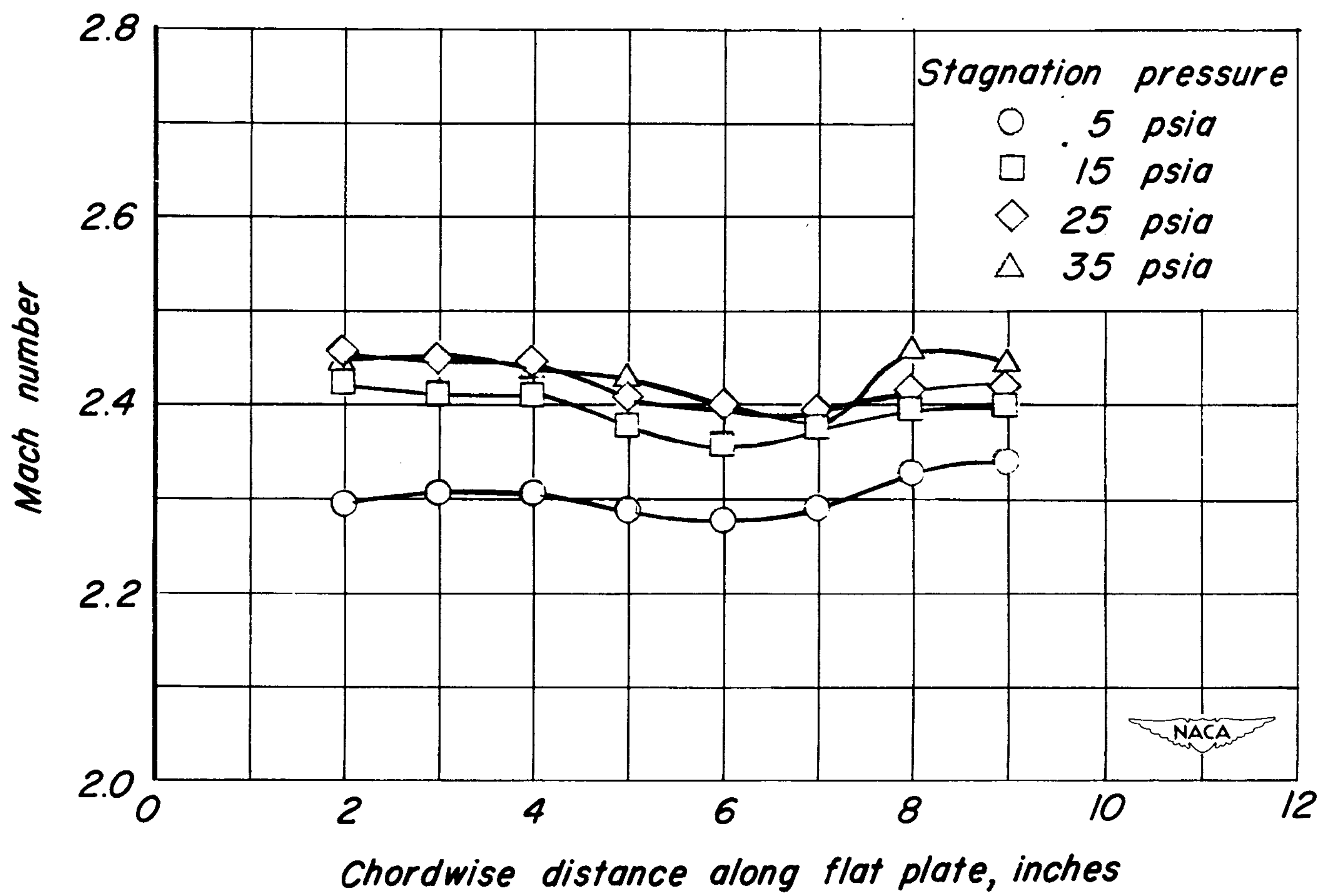
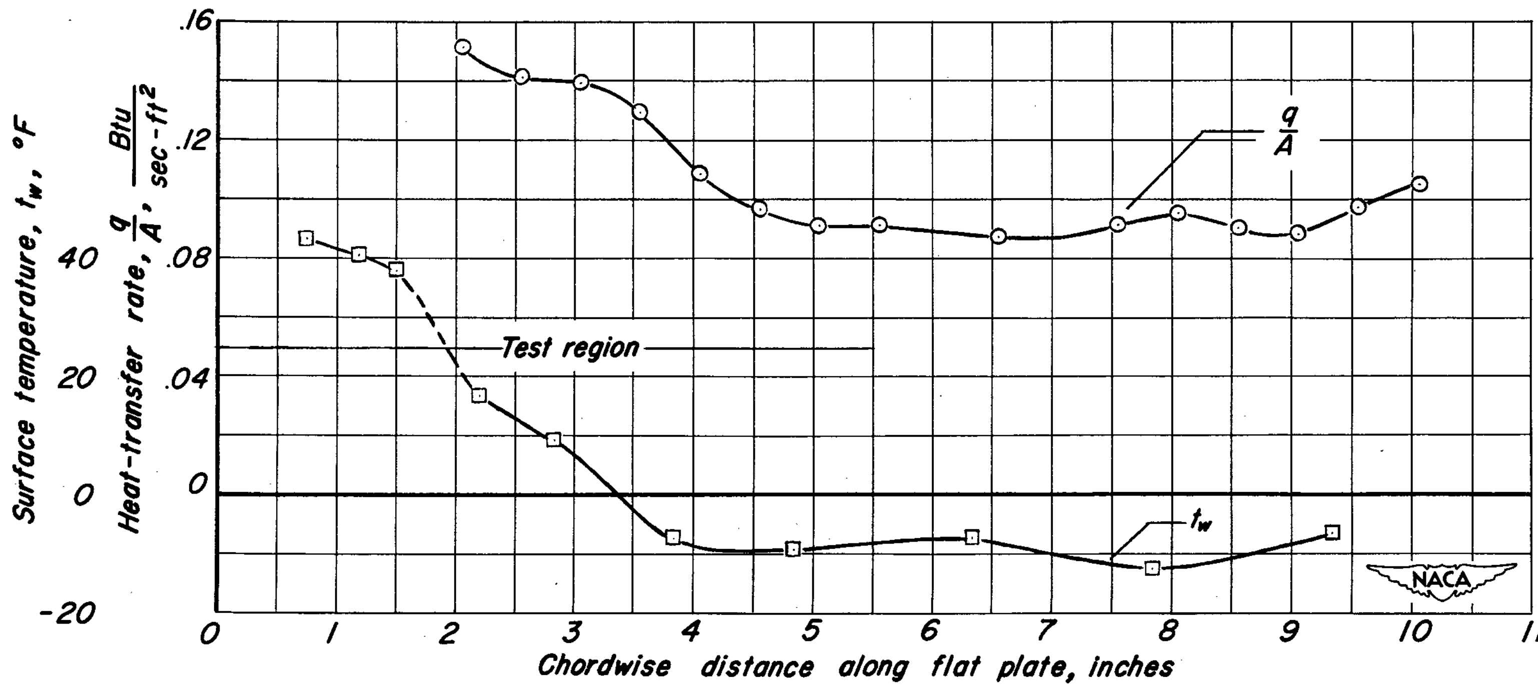
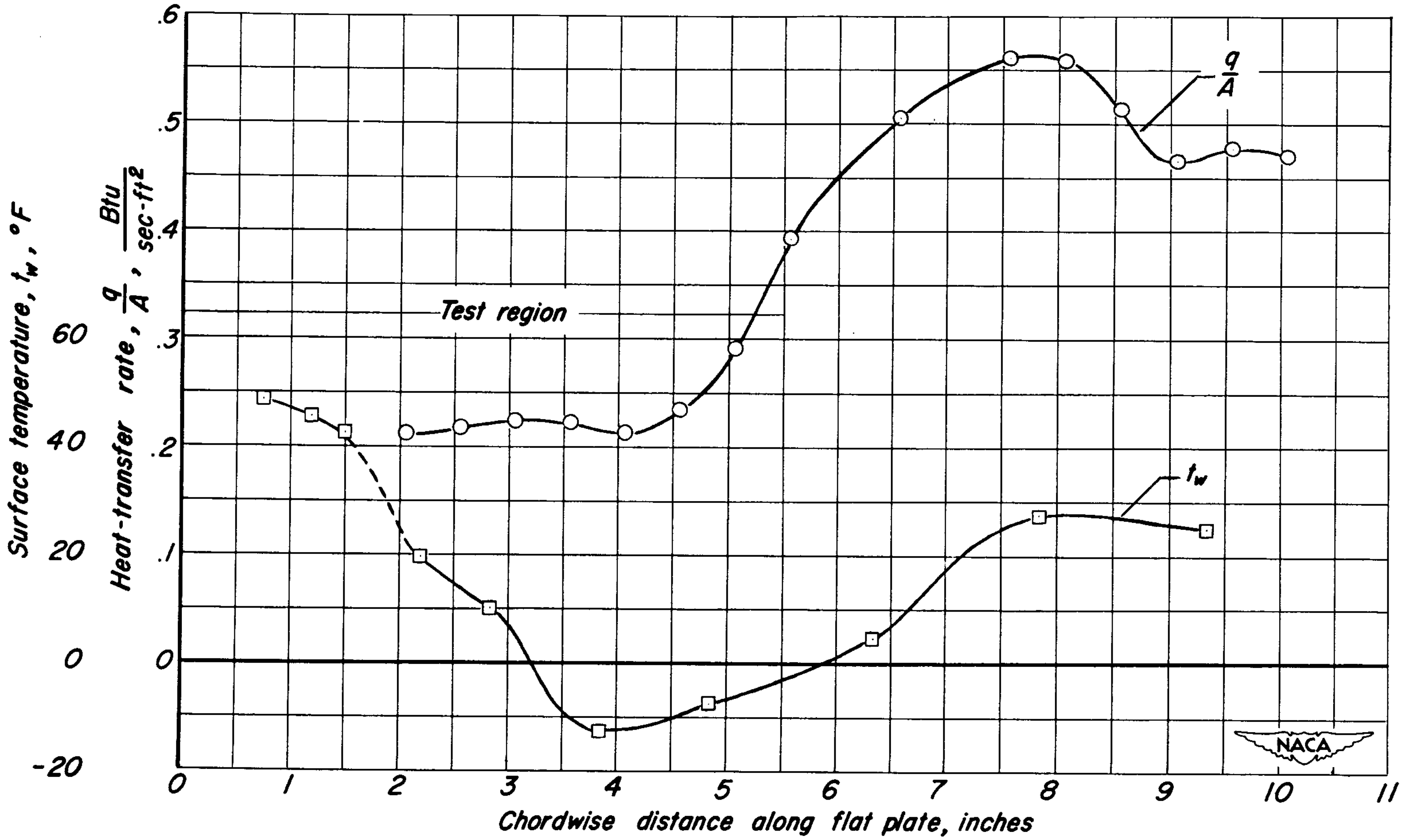


Figure 2. - Mach number distribution along flat-plate model.



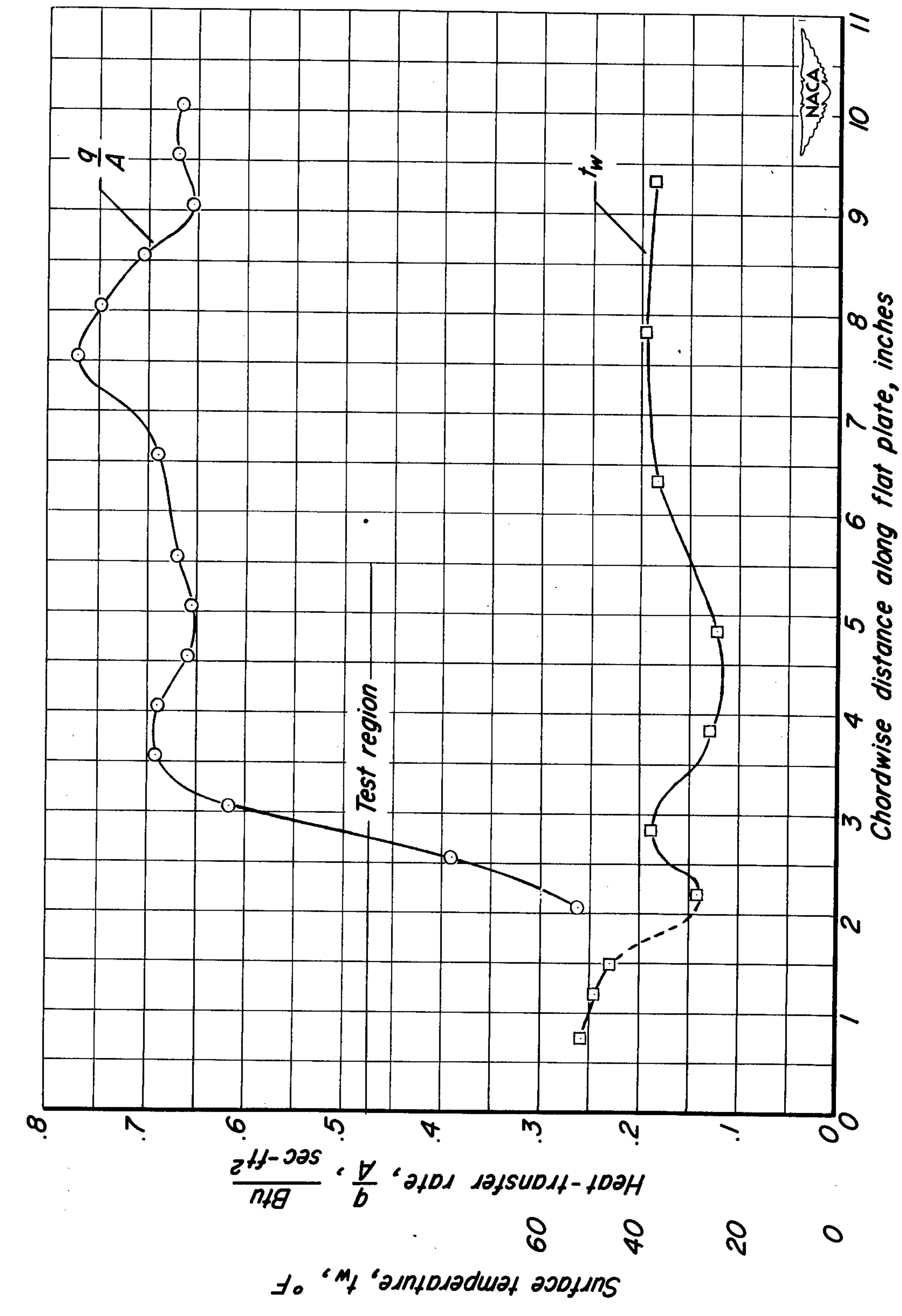
(a) Stagnation pressure, 6 psia.

Figure 3. — Representative heat-transfer rates and surface-temperature distributions along flat-plate model.



(b) Stagnation pressure, 16 psia.

Figure 3.— Continued.



(c) Stagnation pressure, 36 psia.

Figure 3.—Concluded.

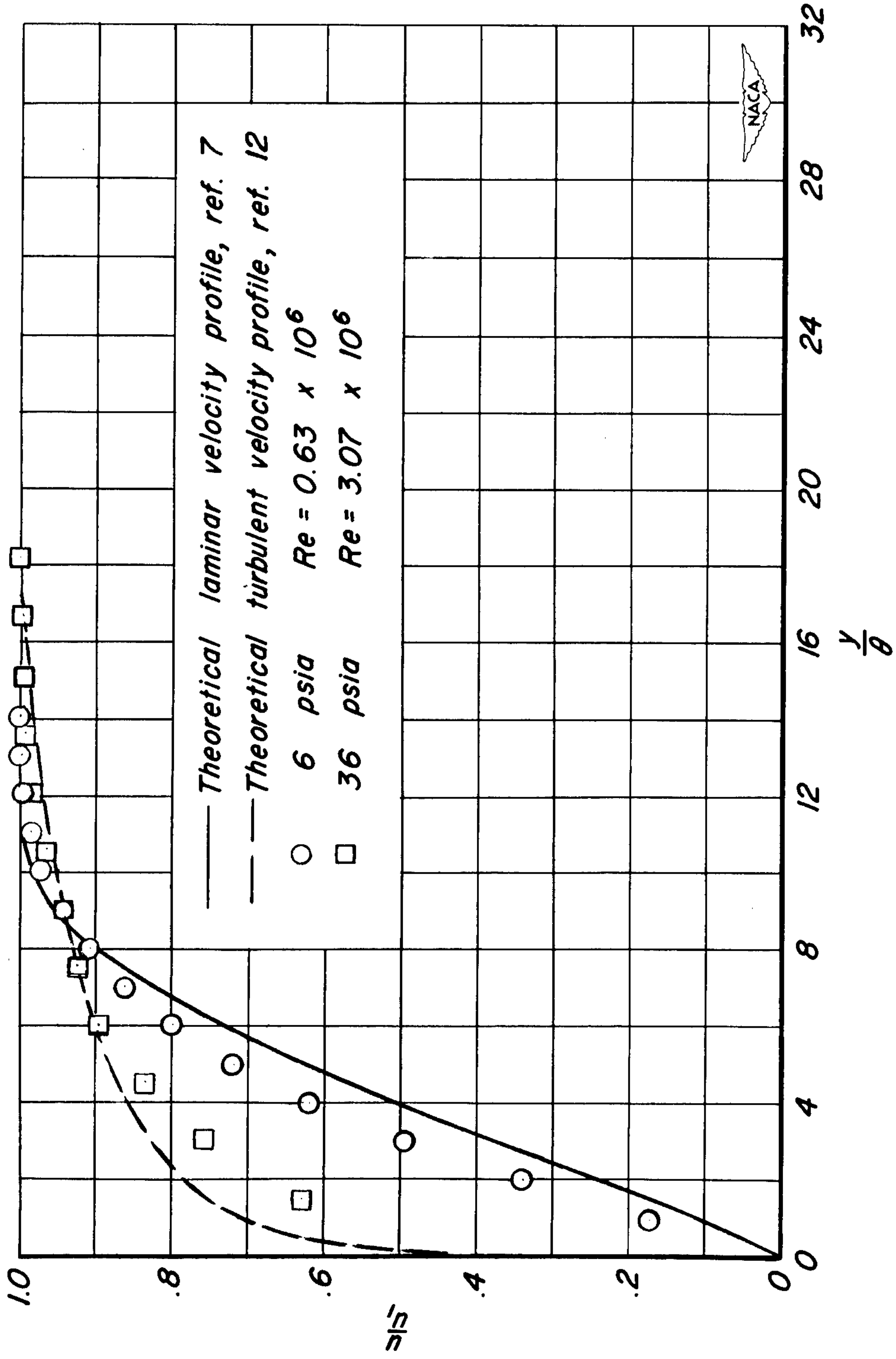
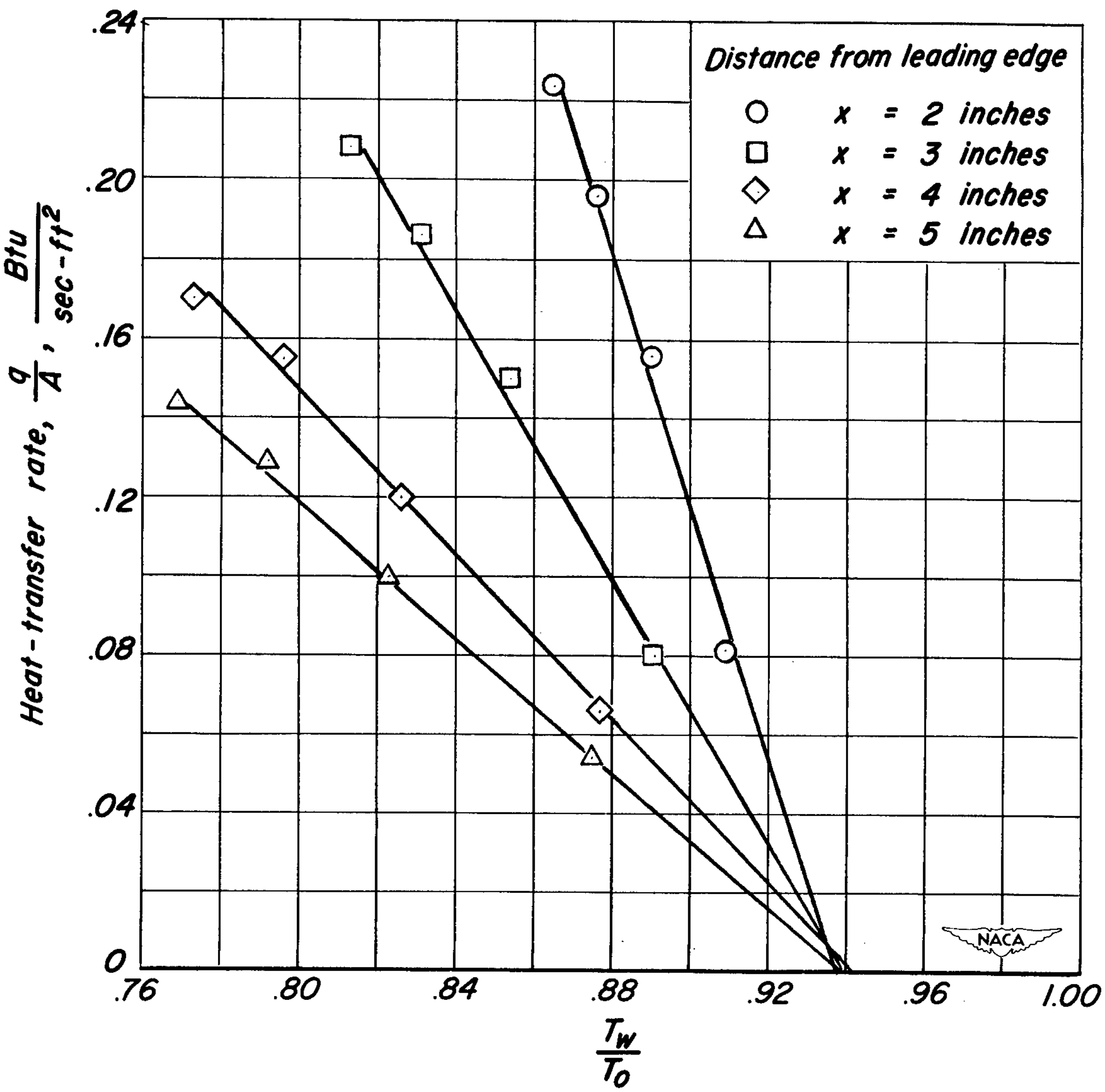
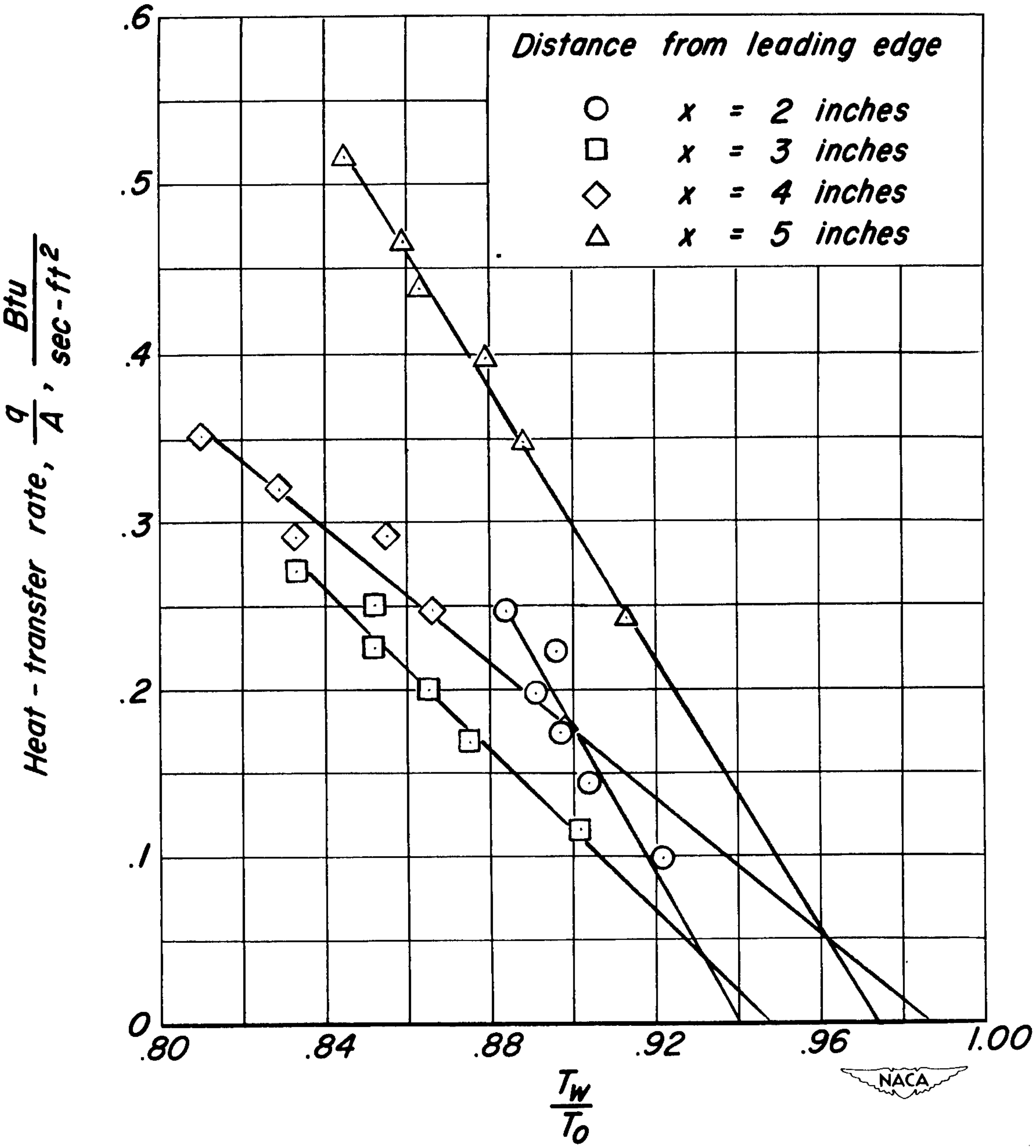


Figure 4. – Velocity-distribution curves for identifying boundary-layer types.



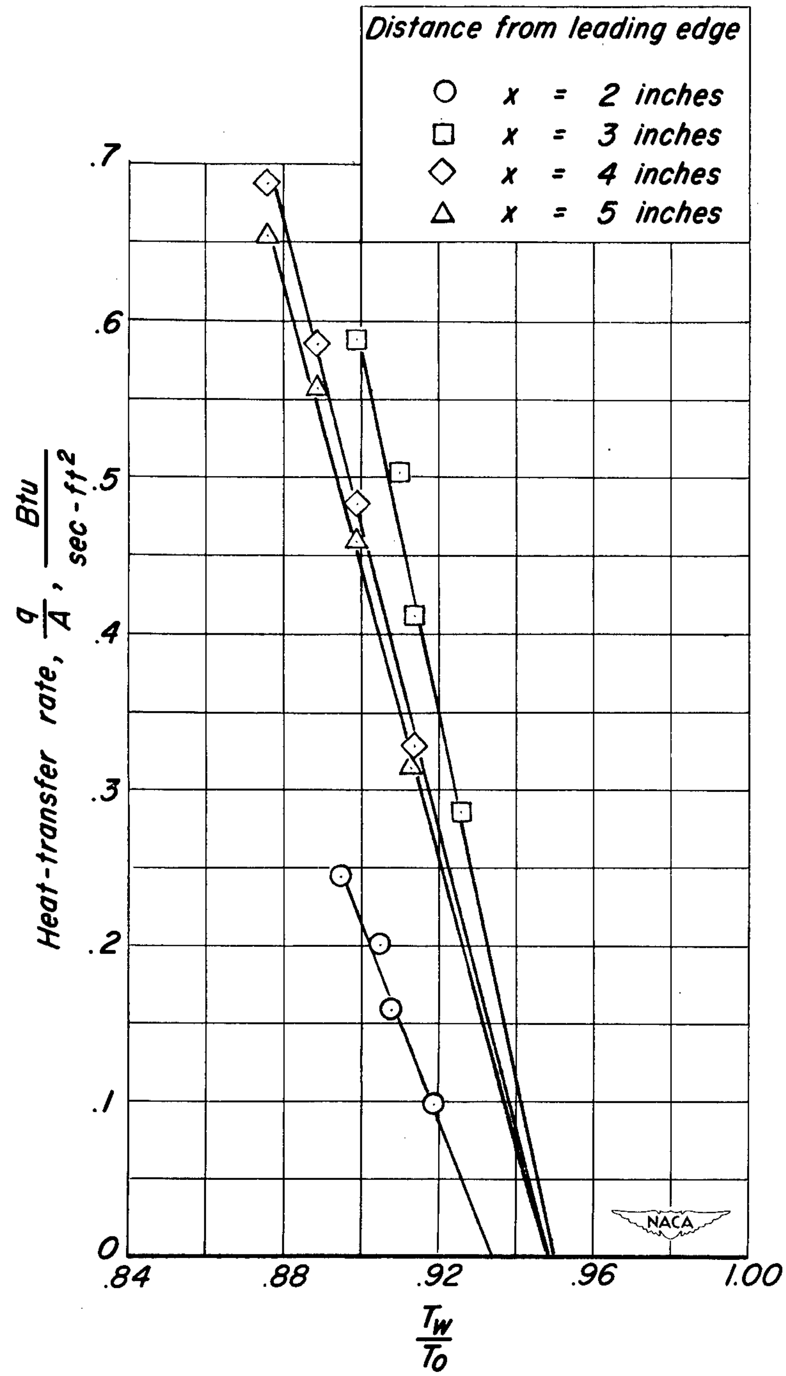
(a) Stagnation pressure, 8 psia.

Figure 5.— The variation of heat-transfer rates with the ratio of surface temperature to stagnation temperature.



(b) Stagnation pressure, 20 psia.

Figure 5.— Continued.



(c) Stagnation pressure, 36 psia.

Figure 5.- Concluded.

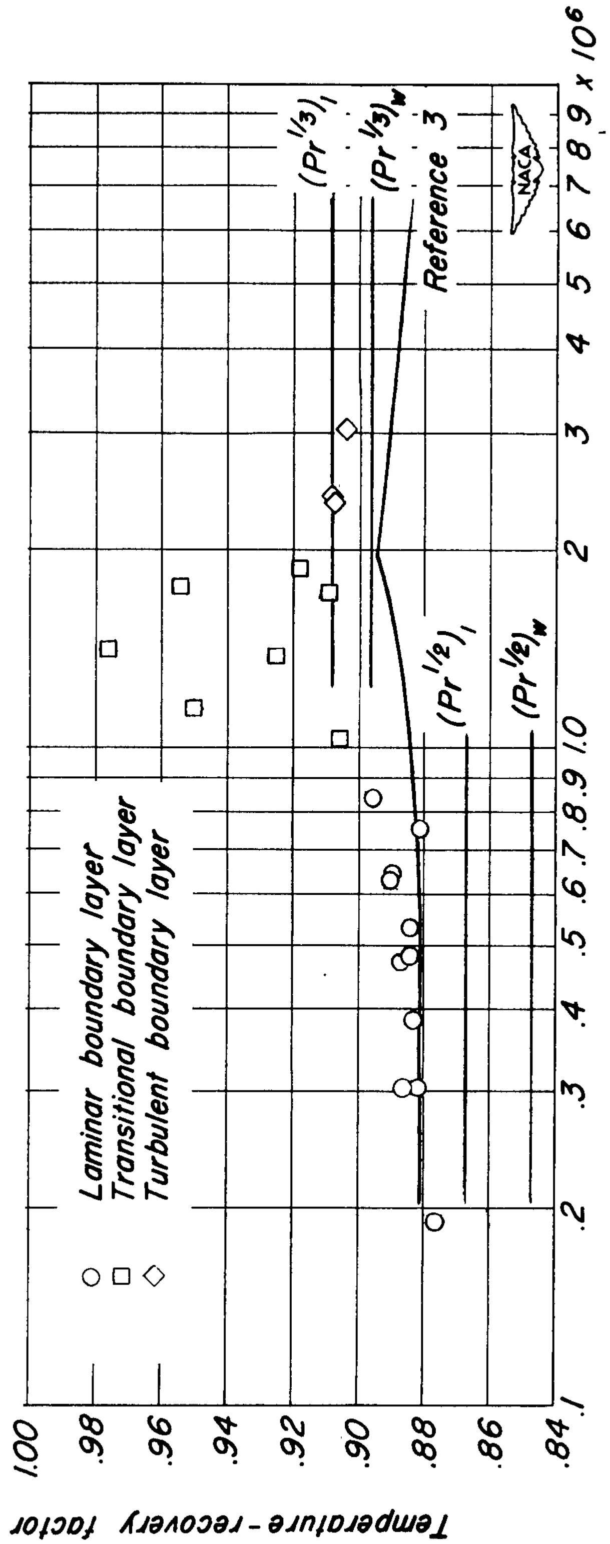


Figure 6. — Temperature-recovery factors on flat-plate model.

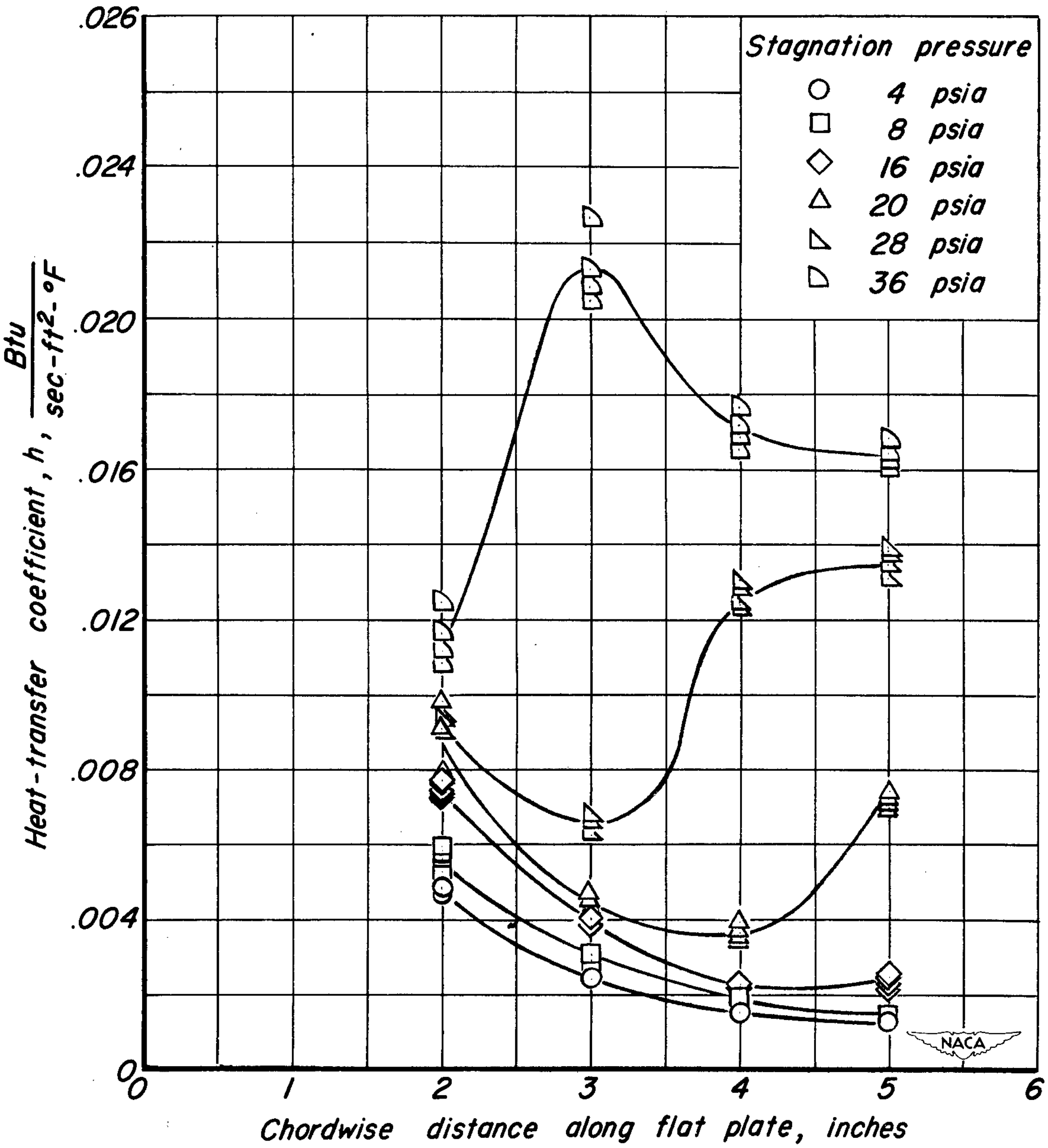


Figure 7. — Experimental heat-transfer coefficients along flat plate.

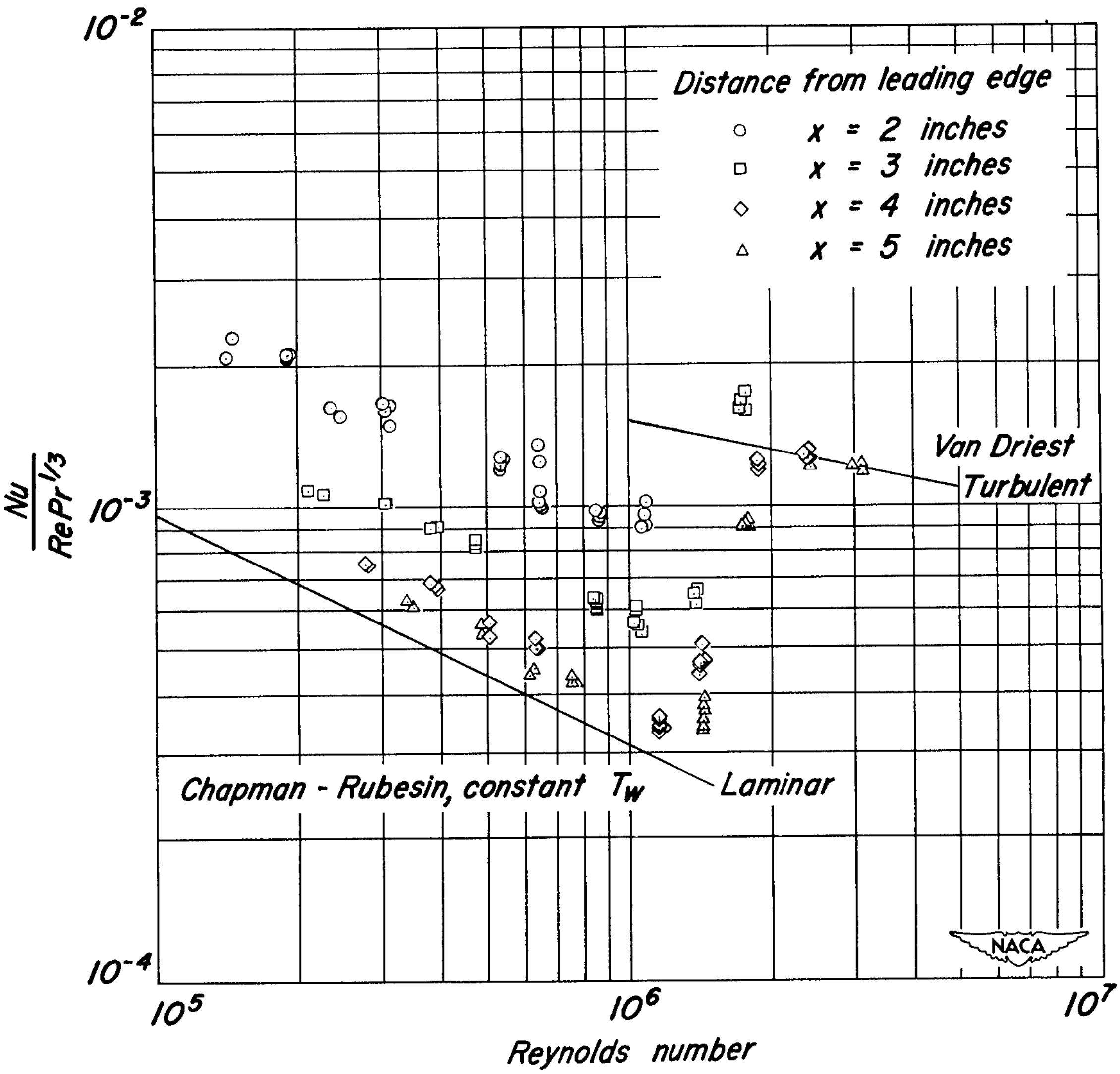


Figure 8. – Dimensionless representation of heat-transfer data.

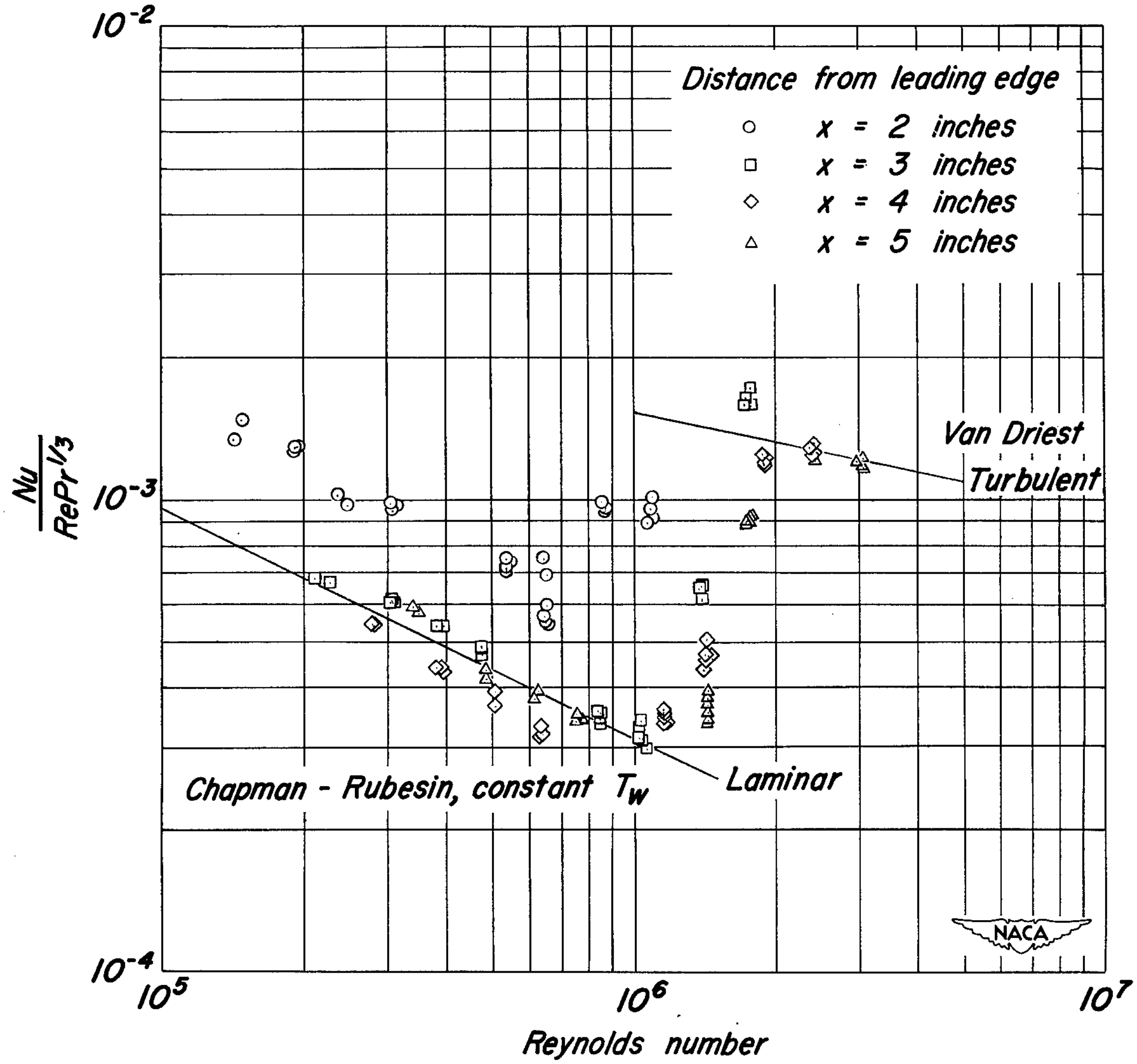


Figure 9. — Dimensionless representation of heat-transfer data referred to the case of constant-surface temperature.

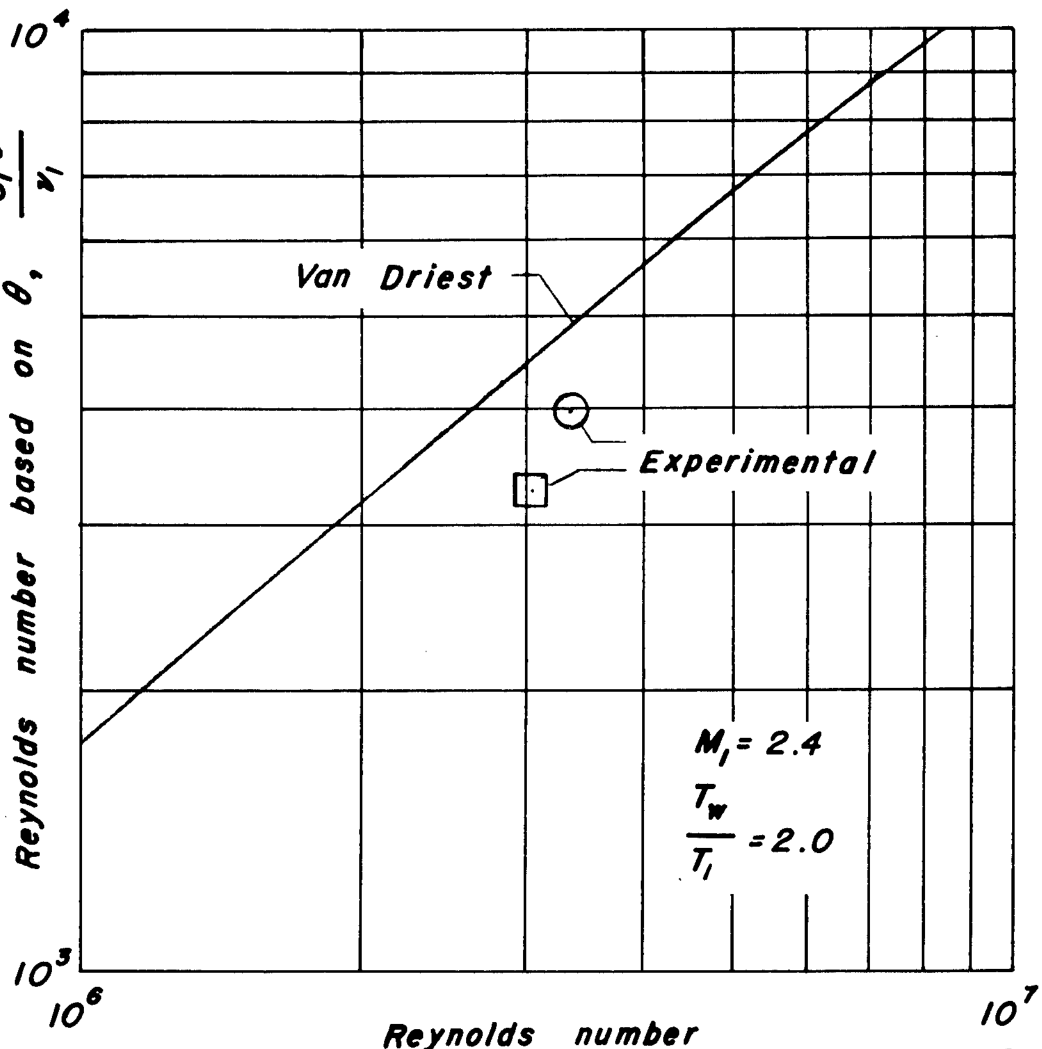


Figure 10.— Reynolds number based on θ as a function of Reynolds number based on x for turbulent boundary layer.

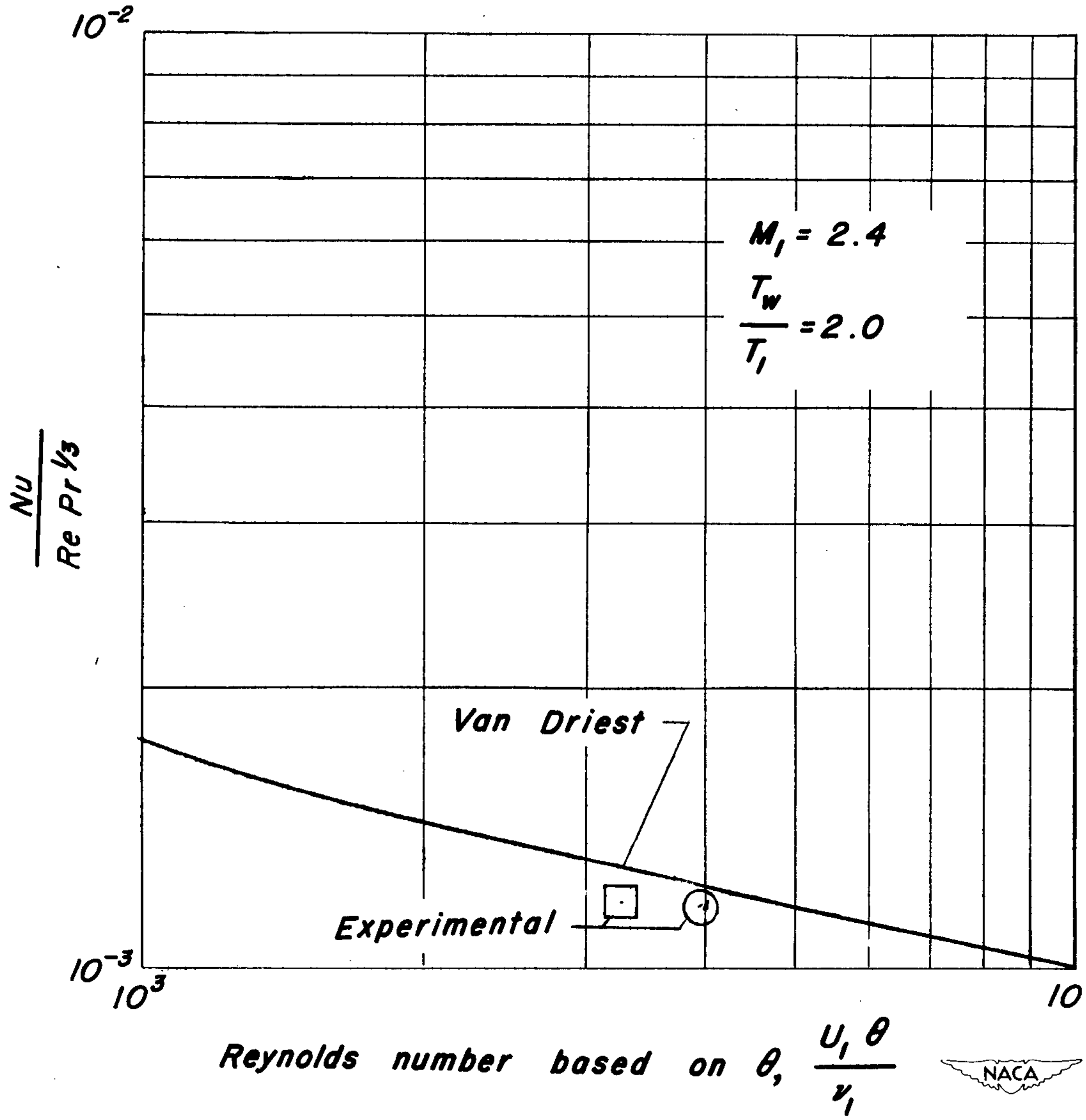


Figure 11. — Dimensionless representation of heat-transfer data for turbulent boundary layer.

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NACA TN 2686
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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER THROUGH LAMINAR AND TURBULENT BOUNDARY LAYERS ON A COOLED FLAT PLATE AT A MACH NUMBER OF 2.4. Ellis G. Slack. April 1952. 31p. diagrs. (NACA TN 2686)

Wind-tunnel tests of the heat-transfer characteristics for laminar and turbulent boundary layers on a cooled flat plate were conducted at a Mach number of 2.4. Data were obtained for a Reynolds number range of 1.5×10^5 to 3×10^6 and for a surface-temperature range of -40° F to 45° F with recovery temperature of the order of 65° F. The temperature-recovery factors agreed well with previous flat-plate results. The heat-transfer results were obtained with negative temperature gradients along the surface and, when related to the constant-surface-temperature case, were, in general, in good agreement with theory.

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1. Flow, Laminar (1.1.3.1)
2. Flow, Turbulent (1.1.3.2)
3. Aerodynamics with Heat (1.1.4)
4. Heating, Aerodynamic (1.1.4.1)
5. Heat Transfer, Aerodynamic (1.1.4.2)
6. Heat, Additions of - Aerodynamic (1.1.4.3)

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